Melting of carbon under extreme conditions characterized by X-ray scattering

D. Kraus[*1], V. Bagnoud[2], A. Blazevic[2], A. Frank[3], D. O. Gericke[4], G. Gregori[5], A. Ortner[1], A. Otten[1], F. Roth[1], G. Schaumann[1], K. Siegenthaler[1], J. Vorberger[4], F. Wagner[1], K. Wünsch[4], and M. Roth[1]*

[1]TU Darmstadt, Germany; [2]GSI, Darmstadt, Germany; [3]Helmholtz-Institut Jena, Germany; [4]University of Warwick, UK; [5]University of Oxford, UK

Introduction

X-ray scattering is a very powerful technique to study warm dense matter which means materials around solid density and temperatures of from several thousand to several hundred thousand kelvins [1]. It gives the possibility for the direct measurement of plasma parameters like temperature, density of free electrons, degree of ionization and the microscopic structure of a warm dense matter sample. Therefore, X-ray scattering is a central diagnostics for all three upcoming plasma physics experiments at FAIR (HIHEX, LAPLAS, WDM) which aim for a precise characterization of warm dense matter [2]. Hence, the accumulation of experience with X-ray scattering experiments at GSI and using the laser system PHELIX as pulsed X-ray source of high brilliance is of major importance for the success of these future experiments at FAIR.

Experiment

After a first successful proof-of-principle experiment on X-ray scattering from shock-compressed matter at GSI in 2011 [3], an advanced campaign was performed in February/March 2012 at the Z6 experimental area. The aim was to investigate the microscopic structure of carbon at the melting regime around 100 GPa (=1 Mbar) pressure. The laser system nhelix with pulse energies of 65 J at 1064 nm and pulse durations of 10 ns was used for the compression of graphite samples. The ns-option of the PHELIX system at Z6 (150 J, 1 ns, 527 nm) was focused on a Ti foil and created enough X-rays of Ti-He-α line radiation (4.75 keV) for a successful X-ray scattering experiment. In fact, a conversion efficiency of up to 5×10^{-3} could be achieved. The scattering angles were chosen to be 105° and 125° which ensures scattering in the non-collective regime (scattering on single electrons). Comparing the intensity of elastic scattering from tightly bound electrons to inelastic scattering from weakly bound electrons gives the possibility to determine an absolute value of the atomic/ionic structure factor S_{ii} of the shocked samples (see figure 1). Density and pressure inside the shock wave could be characterized by a classical measurement of shock and particle velocity resulting in 3.9±0.2 g/cm^3 and 145±17 GPa for the 2012 campaign as well as 3.9±0.2 g/cm^3 and 86±11 GPa for the 2011 campaign.

* d.kraus@gsi.de

Simulations and results

In addition to the experiment, DFT-MD simulations calculating the microscopic structure of possible carbon phases which might be present inside the laser-driven shock have been perforemd. Comparing the experimentally obtained strucutre factors to the simulations gives the definite result that liquid carbon is present inside the laser-driven shock in both experiments [4]. This is in fact the first direct measurement which proves the existence of the liquid phase in this density and pressure regime and can be used to test corresponding theoretical phase diagrams. Thus, a successful method to characterize phase transitions in warm dense matter has been developed. Concerning the carbon solid-liquid phase transition, more sophisticated experiments at the VULCAN laser are scheduled for February/March 2013 and high precision experiments at the LCLS facility are proposed for end of 2013.

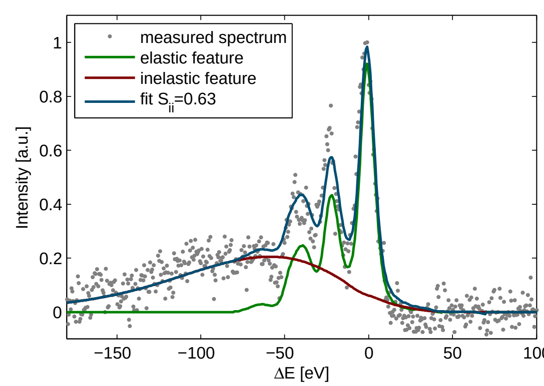

Figure 1: X-ray scattering spectrum from which the structure factor is deduced by determining the ratio of elastic and inelastic scattering. The elastic scattering profile is given by the source radiation spectrum which was measured in the experiment whereas the inelastic feature consists of the convolution of the source spectrum and a typical Compton profile of bound electrons.

References

[1] S. H. Glenzer, R. Redmer, Rev. Mod. Phys. 81, 1625 (2009)

[2] FAIR Baseline Technical Report (2006)

[3] D. Kraus et al., High Energy Density Physics 8, 46-49 (2012)

[4] D. Kraus et al., in preperation